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On the reported magnetic precursor of the 1993 Guam earthquake

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[1] Using 1-second magnetometer data recorded 67 km from the epicenter of the 1993 M_w 7.7 Guam earthquake, Hayakawa et al. (1996) and Miyahara et al. (1999) identify anomalous precursory changes in ultra-low frequency magnetic polarization (the ratio of vertical to horizontal field components). In a check of their results, we compare their data (GAM) with 1-second data from the Kakioka observatory (KAK) in Japan and the global magnetic activity index *Kp*. We also examine log books kept by USGS staff working on the Guam magnetic observatory. We find (1) analysis problems with both Hayakawa et al. and Miyahara et al., (2) significant correlation between the GAM, KAK, and *Kp* data, and (3) an absence of identifiable localized anomalous signals occurring prior to the earthquake. The changes we do find in polarization are part of normal global magnetic activity; they are unrelated to the earthquake. **Citation:** Thomas, J. N., J. J. Love, M. J. S. Johnston, and K. Yumoto (2009), On the reported magnetic precursor of the 1993 Guam earthquake, *Geophys. Res. Lett.*, *36*, L16301, doi:10.1029/2009GL039020.

1. Introduction

[2] The M_w 7.7 Guam earthquake of 8 August 1993 [*Campos et al.*, 1996] injured 48 people and caused more than $100 million of damage. The work of *Hayakawa et al.* [1996] and *Miyahara et al.* [1999] appear to support the possibility that this earthquake could have been predicted. From their analyses of the ratio of vertical-to-horizontal magnetic-component data acquired in the ULF (ultra-low frequency, <10 Hz) range from ground-based magnetometers located near the earthquake epicenter, Hayakawa et al. and Miyahara et al. identify anomalous signals occurring prior to the earthquake. Together, these two reports are among the most frequently cited in the literature of earthquake prediction, with over 68 published citations recorded by Google Scholar as of June 2009.

[3] The Guam magnetic-precursor reports followed reports of a different type of magnetic precursor for the 1989 M_w 7.1 Loma Prieta earthquake [*Fraser-Smith et al.*, 1990; *Bernardi et al.*, 1991]. Subsequently, other reports of magnetic precursors have been published [*Hayakawa et al.*, 2000; *Uyeda et al.*, 2002; *Hayakawa et al.*, 2007]. Unfortunately, what has been lacking is a convincing physical explanation for their cause [e.g., *Park et al.*, 1993; *Johnston*, 1997], and specific results for one earthquake have not been typically reproduced for another earthquake [e.g., *Fraser-Smith et al.*, 1994; *Johnston et al.*, 2006]. Recently, the validity of the reported Loma Prieta precursor has been questioned [*Thomas et al.*, 2009; *Campbell*, 2009]. And, as with many aspects of earthquake prediction [e.g., *Geller*, 1991; *Normile*, 1994; *Campbell*, 1998], the subject of magnetic precursors remains controversial.

[4] Given the importance of earthquake prediction, reports of earthquake precursors need to be analyzed and checked for reproducibility. This is especially true for prominent reports like those for the 1993 Guam earthquake. Therefore, in this report we examine the reports of *Hayakawa et al.* [2000] and *Miyahara et al.* [1999], separately, for their individual validity, and together, for their mutual consistency. We attempt to reproduce their results using the original magnetometer data, and we compare results with auxiliary data sets. We investigate the possibility that the seemingly anomalous Guam signals might actually be normal magnetic activity driven by solar-terrestrial interaction.

2. Data

[5] We analyze four data sets: (1) 3-component 1-second magnetic-field data from the GAM magnetic station (13.6° N, 144.9° E), the same data used by *Hayakawa et al.* [1996] and *Miyahara et al.* [1999]. The GAM data were acquired by a digital fluxgate magnetometer sensor (210-Magnetic Meridian) [*Yumoto et al.*, 1992] located at the Guam USGS magnetic observatory, 67 km from the earthquake epicenter. The GAM system was operated independently of co-located USGS digital and analog systems. (2) 3-component 1-second magnetic-field data from the Kakioka observatory (KAK, 36.2° N, 140.2° E), Japan, 2626 km north of the earthquake. The KAK data were acquired by an optical-pumping sensor during January–May 1993 and by a fluxgate sensor during June–December 1993. (3) The 3-hour global magnetic-activity index *Kp*, derived from magnetometer data from 13 observatories. (4) Operational log books kept by USGS staff working at the Guam magnetic observatory. These anecdotal records are useful for identifying periods of artificial (man-made) interference.

3. Observations of Hayakawa and Miyahara

[6] In the search for earthquake precursors, *Hayakawa et al.* [1996] use magnetic polarization [*Molchanov et al.*, 1992; *Kopytenko et al.*, 1994]. They first band-pass filter the magnetometer data for ultra-low frequencies (0.01–0.05 Hz); they then use the separate time series of the vertical (Z) and horizontal (H) magnetic-vector components to form a polarization (Z/H) ratio time series. This formula

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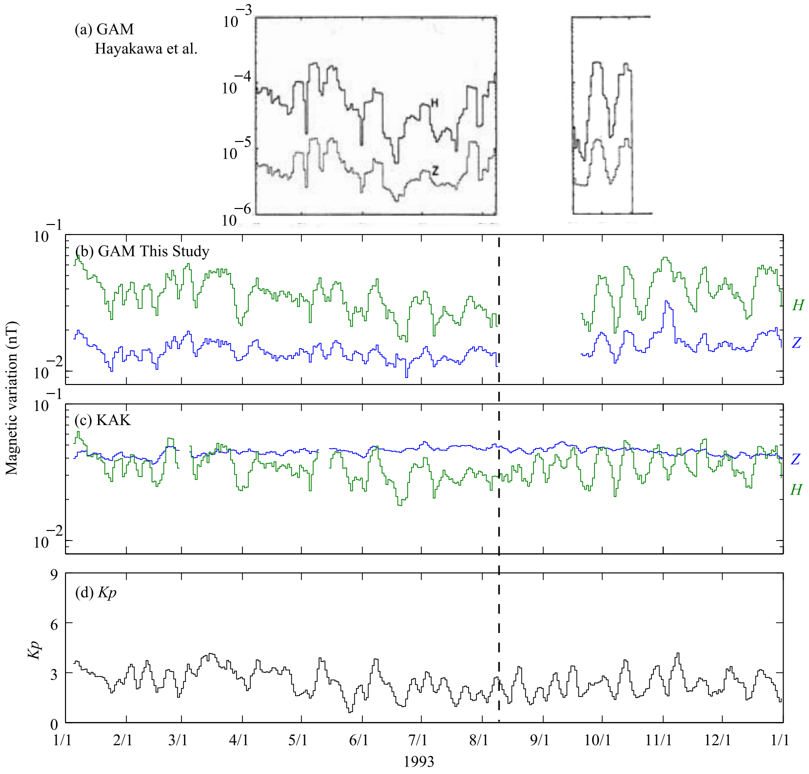

Figure 1. Five-day running means, each calculated once per day, of vertical (Z) and horizontal (H) magnetic-field variation in the 0.01–0.05 Hz frequency band for 1993: (a) Guam (GAM) as determined by *Hayakawa et al.* [1996] (a reproduction of *Hayakawa et al.* [1996, Figure 3]), (b) Guam (GAM) as determined here by following the formula given by Hayakawa et al., and (c) Kakioka (KAK). (d) For comparison, the global magnetic activity index Kp.

for calculating polarization is motivated by standard magnetic-induction methods [*Schmucker*, 1970; *Simpson and Bahr*, 2005], where the objective is the determination of lithospheric electrical conductivity. Simply put, rapid externally-sustained variations in the horizontal magnetic component induce subsurface electric currents, which, in turn, perturb the vertical magnetic component. If the electrical conductivity in the vicinity of a fault changes prior to an earthquake, such as might happen under the changing stress regime during early fault failure [*Lockner and Byerlee*, 1986], then changes in polarization might be detected. It is necessary to minimize the effects of day-side micropulsations that are caused by solar-terrestrial interaction [*Jacobs*, 1970; *Kangas et al.*, 1998]. For this reason, Hayakawa et al. only use data that are centered on local midnight (12:00–16:00 UT for Guam). It should be emphasized, however, that selecting this subset of the data does not completely eliminate solar-terrestrial effects. To reduce spurious noise, Hayakawa et al. use 5-day-running-means of Z and H, calculated once per day – reproduced here in Figure 1a. These quantities were then used to form 5-day-means of polarization (Z/H), also calculated once per day, reproduced here in Figure 2a.

[7] The most important observation by *Hayakawa et al.* [1996], highlighted with a fitted trend in Figure 2a, is an apparently anomalous increase in the polarization time series. It rises from a baseline of about 0.03 on 8 April to 0.07 when the earthquake occurred on 8 August. After the earthquake, and after the magnetometer was made operational again on 17 September, the time series resumes at a lower and flat level, similar to that seen in April. Before we continue, the following internal inconsistency in the report of Hayakawa et al. is noted: the Hayakawa et al. values of Z and H, Figure 1a, do not agree with their ratio Z/H, Figure 2a. Specifically, on 1 August, Z is about 3×10^{-6} and H is about 2×10^{-5} (each in unspecified units), so Z/H should be about 0.15, but their Z/H value is about 0.07. Confusingly, they label the polarization as “relative”, even though the quantity is dimensionless, and we wonder whether this might be related to the inconsistency.

[8] The *Miyahara et al.* [1999] analysis of the GAM data appeared in a book edited by Hayakawa. Other than selecting a slightly different range of frequencies (0.01–0.10 Hz), they processed the data according to the formula given by *Hayakawa et al.* [1996]. Therefore, we might expect consistent results. What we observe are inconsistencies. These are most prominently seen in comparisons of *Miyahara et al.* [1999, Figure 3] and *Hayakawa et al.* [1996, Figure 5].We enumerate the differences: (1) Prior to the earthquake, Miyahara et al. find values of Z/H ranging from about 0.20 to 0.70; Hayakawa et al. find values ranging from 0.03 to 0.07 in unspecified units. (2) Prior to the earthquake Miyahara et al. find an increasing trend in Z/H that is more gradual than that found by Hayakawa et al. (3) Prior to the earthquake and for a week centered on 27 July, Miyahara et al. find an abrupt positive offset in Z/H; Hayakawa et al. find no such offset. (4) After the earthquake and after the magnetometer was again operational on 17 September, Miyahara et al. find a gradually decreasing trend in Z/H; the trend found by Hayakawa et al. is flat.

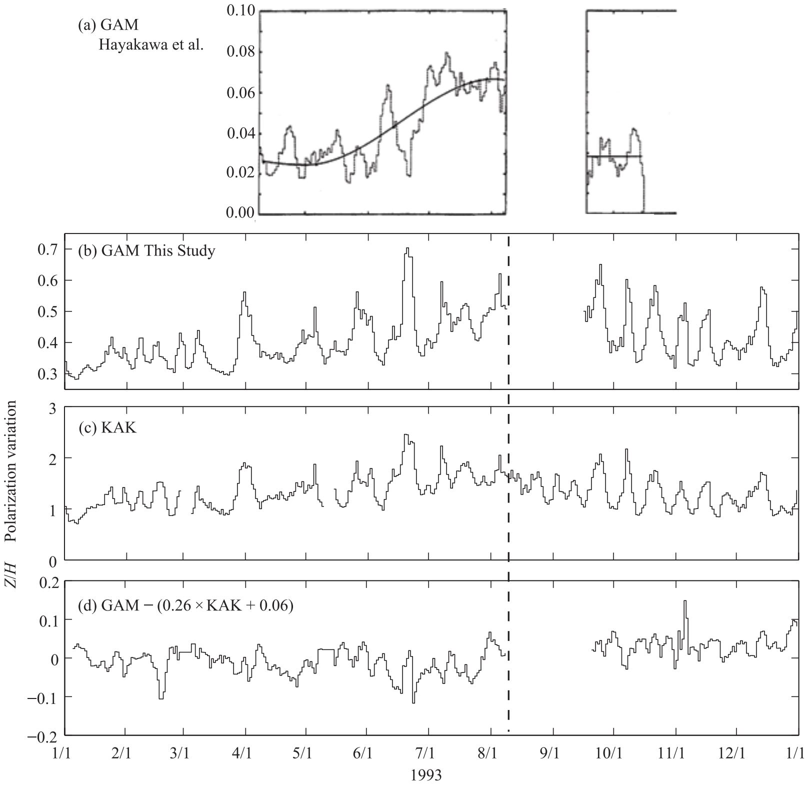

Figure 2. Five-day running means, each calculated once per day, of the polarization ratio (*Z/H*) in the 0.01–0.05 Hz frequency band for 1993: (a) Guam (GAM) as determined by *Hayakawa et al.* [1996] (a reproduction of *Hayakawa et al.* [1996, Figure 5]), (b) Guam (GAM) as determined here by following the formula given by Hayakawa et al., and (c) Kakioka (KAK). Note the high degree of correlation between the GAM (Figure 2b) and KAK (Figure 2c) polarization time series. (d) Amplitude corrected difference of GAM and KAK polarization ratios. Note that the amplitude of the residual is essentially flat and of small amplitude compared to the signal in Figure 2b.

[9] The Guam precursor observations of *Hayakawa et al.* [1996] and *Miyahara et al.* [1999] do not resemble the Loma Prieta precursor observations of *Fraser-Smith et al.* [1990] and *Bernardi et al.* [1991]. Although there is significant overlap in the frequencies analyzed, neither Hayakawa et al. nor Miyahara et al. observe prominent noise in the raw data time series like that seen prior to the Loma Prieta earthquake. Instead, Hayakawa et al. and Miyahara et al. only report the identification of precursors after the data have been processed. Although not likely, this inconsistency might be due to the fact that the magnetic-field component (magnetic east) analyzed by Fraser-Smith et al. is orthogonal to the polarization components (magnetic north and down) used by Hayakawa et al. and Miyahara et al. The inconsistency might also be due to local geological differences. In any case, it is worth recognizing that the type of precursory observations reported for the Loma Prieta earthquake has not been reproduced in the Guam reports.

4. A Re-examination of the GAM Data

[10] In conducting our own analysis, we processed the GAM data according to the detailed formula of *Hayakawa et al.* [1996]. In Figure 1b we show 5-day running means (calculated once per day) of the *Z* and *H* magnetic-field components; our presentation of the entire year of 1993 gives a panoramic view of the data that is broader than that provided by *Hayakawa et al.* [1996] (Figure 1a). Here we see that variations in *Z* and *H* are generally well correlated with each other: correlation coefficient 0.88 before (0.83 after) the earthquake. In Figure 1d we see that *H* is generally correlated with the 5-day running mean of the global activity index *Kp*: 0.73 before (0.57 after). Recognizing that *Kp* is defined in terms of *H* variation, albeit at frequencies much lower than ULF, it is safe to conclude that much of the ULF variation recorded in the *H* GAM data is global in scale and unrelated to the earthquake. On the other hand, detailed correlation in *Z* and *Kp* is lower: correlation coefficient 0.52 before (0.29 after). This is almost certainly related to the fact that *Kp* is not defined in terms of observatory *Z* data, since this component is sensitive to localized differences in lithospheric electrical conductivity.

[11] Although *Hayakawa et al.* [1996] report their *Z* and *H* time series in unspecified relative units and we report ours in nano-Teslas (nT), we can compare general trends in both data sets before and after the earthquake, Figures 1a and 1b. In the months before the earthquake, the details and trends for the two versions of *Z* and *H* are similar, but a notable difference is seen for the two or three weeks prior the earthquake: Hayakawa et al. find an abrupt enhancement

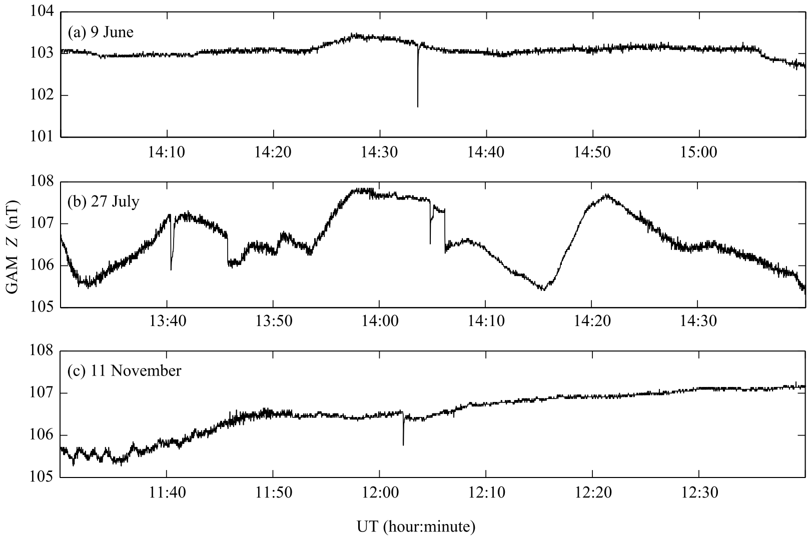

Figure 3. Seventy minutes of Guam (GAM) data from (a) 9 June, (b) 27 July, and (c) 11 November 1993. Spikes are seen in each time period. The data in Figure 3b were reported by *Miyahara et al.* [1999] (similar to *Miyahara et al.* [1999, Figure 5]) and are from 12 days prior to the earthquake. The data in Figure 3a are from before the earthquake and in Figure 3c are from after the earthquake.

of variation in both the Z and H. We do not find such an enhancement.

[12] While observations for the individual Z and H traces provide insight, it is the polarization ratio Z/H that is of more interest here. Consistent with *Hayakawa et al.* [1996] (Figure 2a), we find that Z/H tends to increase prior to the earthquake (Figure 2b), but the details of the polarization time series are very different, especially in the weeks after 1 July, and just prior to the earthquake; we do not find the distinctive enhancement in polarization that Hayakawa et al. find. After the earthquake the trend in our polarization time series is clearly downwards, while for Hayakawa et al. it is flat. In some respects our results are in better agreement with those obtained by *Miyahara et al.* [1999, Figure 3], an increasing trend in polarization prior to the earthquake and a decreasing trend after the earthquake, although we do not find a peak (as they do) on about 27 July just 13 days prior to the earthquake.

[13] Next, we examine some difficulties in the analysis of *Miyahara et al.* [1999]. They focus on spikes and offsets in the Z component of the GAM data (our Figure 3 and *Miyahara et al.* [1999, Figure 5]), concluding that the odd variations occurring on 27 July are due to crustal electric currents arising from compressive stress. Looking at a long duration of the GAM data, we found similar oddities both before the "precursory" period, Figure 3a for 9 June, as well as long after the earthquake, Figure 3c for 11 November. Furthermore, in 1993 a USGS staff member working on the Guam observatory kept daily records of these data incidents, and he understood them to be related to anti-corrosive electric currents that the U.S. Air Force was applying to nearby pipelines (P. M. Hattori, personal communication, July 2008). In developing the USGS Geomagnetism Program's final data products, spikes and offsets similar to those shown in Figure 3 were removed from the 1-minute USGS Guam data (which are independent of the GAM data) during routine data processing, since they were identified as spurious. Artificial perturbations in the data are probably responsible for some of the anomalies found by Miyahara et al.

5. Comparisons With KAK

[14] As the final step in our analysis, we examine 1-second data from Kakioka, Japan, and compare them with the GAM data. Following the formula given by *Hayakawa et al.* [1996], we processed the KAK data in the same way as the GAM data were processed. In Figure 1c we show 5-day running means of the KAK Z and H components. Close inspection shows good correlation of the KAK and GAM H time series: 0.95 before (0.79 after); and less correlation between the Z time series: 0.06 before (-0.12 after). With respect to KAK correlation with Kp, for H it is high: 0.71 before (0.66 after); and for Z it is low: -0.23 before (-0.01 after). Again, it is apparent that most of the ULF variation in H KAK data is global in scale, while Z has a more localized variation.

[15] The KAK polarization ratio Z/H is shown as a 5-day running mean in Figure 2c. Although there is a difference in amplitude between the KAK and GAM polarizations, as we would expect for data coming from such different magnetic latitudes, the correlation is excellent: 0.93 before (0.94 after) the earthquake. Indeed, in detail the two time series are correlated for periods lasting from weeks to a month or so, and they both show similar longer-term increasing trends prior to the earthquake on 8 August and decreasing trends after the earthquake.

[16] The consistency we find between the KAK and GAM polarization time series in Figures 2b and 2c stands in stark contrast to the most prominent result of Hayakawa et al., shown in Figure 2a. In particular, there is no discernable difference in the trends of the polarization time

series from Guam and Japan. This can be clearly demonstrated in terms of a simple linear relationship, one describing constant proportionality and offset,

$$\mathrm{GAM} = 0.26 \times \mathrm{KAK} + 0.06.$$

The linear residual is shown in Figure 2d; the root-mean square of the residual (0.038) is much smaller than the year-long trend seen in the GAM polarization time series (~0.2). The residual before and after the earthquake is essentially flat and not of the same (relative) magnitude found by Hayakawa et al. We see nothing here that might be appropriately described as anomalous.

6. Conclusions

[17] We conclude that, contrary to previously published reports, the GAM data do not contain signals that might have served as unambiguous indications of the imminent occurrence of the M_w 7.7 Guam earthquake of 8 August 1993. What signal is seen in the data at about the time of the earthquake is part of normal global magnetic-field variation caused by solar-terrestrial interaction. We acknowledge that this might be considered to be a pessimistic result for earthquake prediction. Reproducibility is, of course, a fundamental principle of the scientific method, and obtaining clearly reproducible results remains a difficult goal for the earthquake-prediction research community [*Jordan*, 2006]. The analysis presented here can be regarded as part of a larger communicative process that we hope will soon lead to some resolution on a controversial subject of societal importance.

[18] **Acknowledgments.** We thank S. Abe for providing the GAM 1-second data from the 210-Magnetic Meridian sensor on Guam. We thank M. Nosé and T. Iyemori of the Kyoto World Data Center for supplying the Kakioka data, and we express our appreciation to the Japan Meteorological Agency for supporting the long-term operation of the Kakioka magnetic observatory. We thank R. W. Briggs, A. J. Crone, and J. W. Dewey for reviewing a draft manuscript. We thank P. M. Hattori for his support in operating the Guam USGS observatory. J.N.T. was supported by a USGS Mendenhall Postdoctoral Fellowship.

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